Washington University in St. Louis
James McKelvey School of Engineering

Titanium-Cerium Electrode-Decoupled Redox Flow Batteries Integrated With Fossil Fuel Assets For Load-Following, Long-Duration Energy Storage

Project FE0032011

presented by:

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in collaboration with

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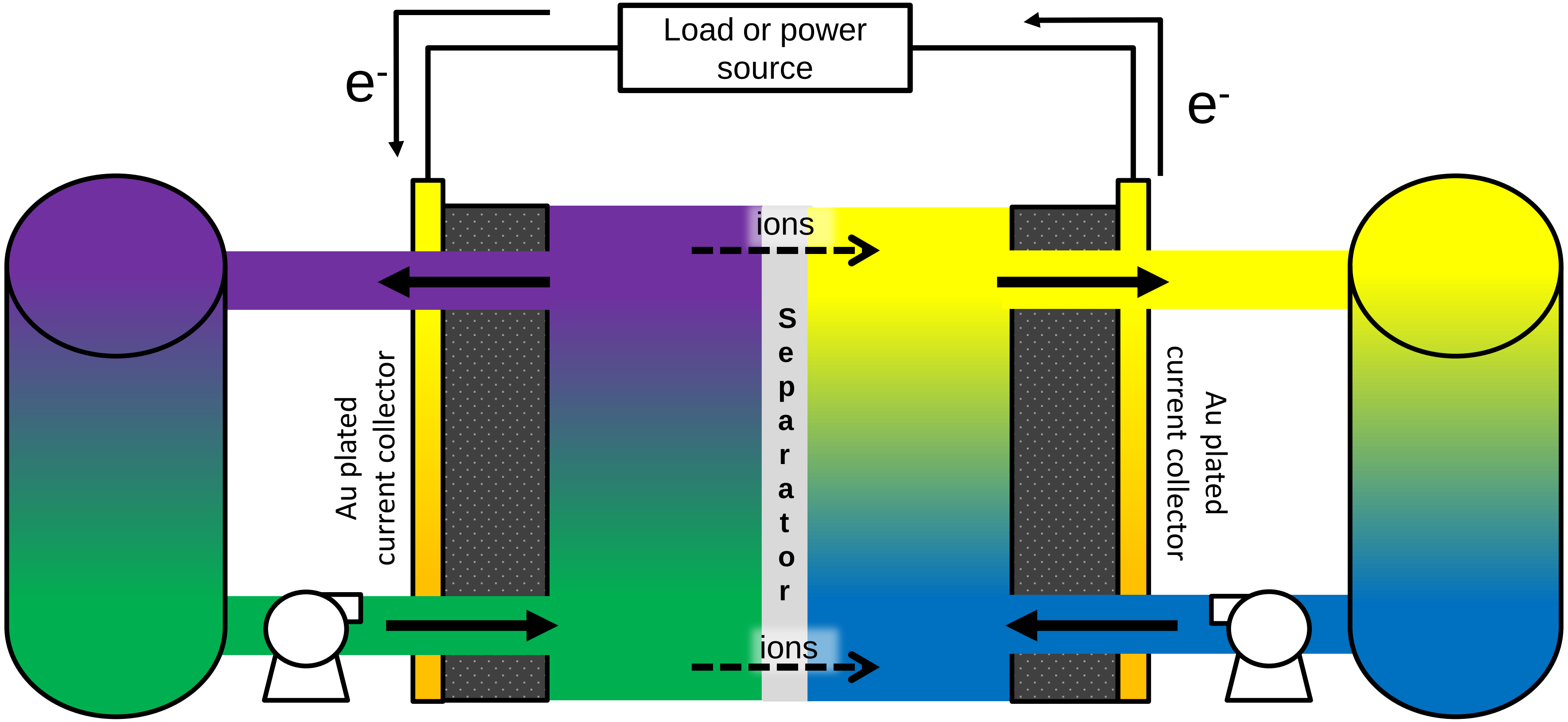
NETL FECM R&D Spring Project Review Meeting April 20, 2023

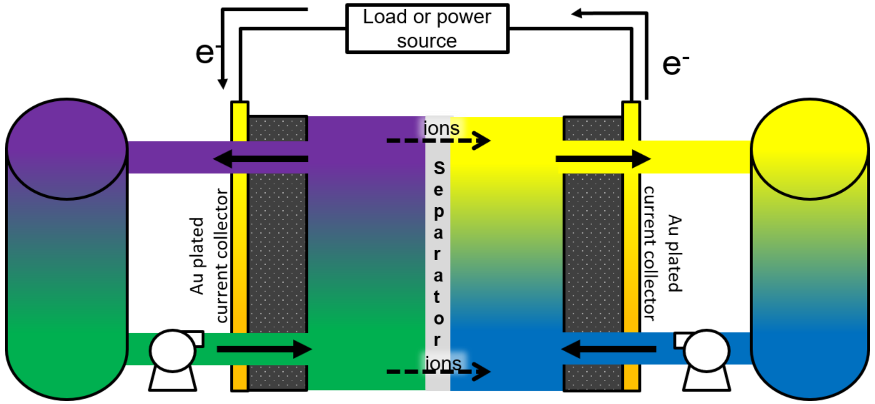
Benefits of RFB Integration with Fossil Assets

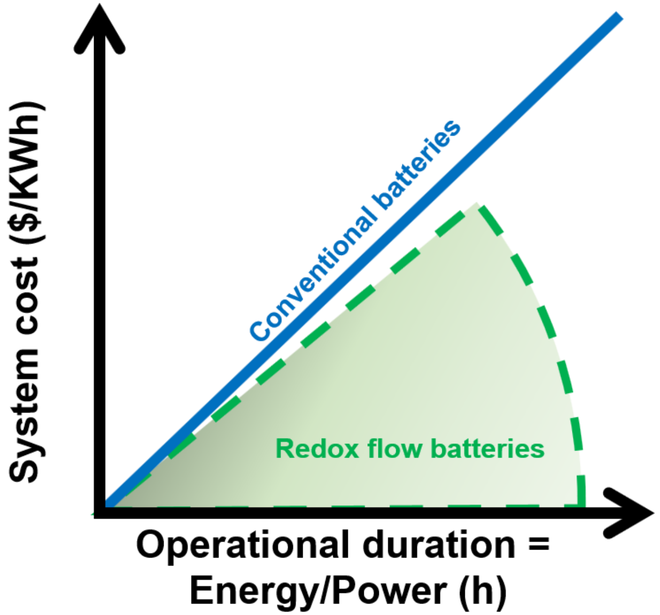
- Increase value of existing fossil plants
- Enhance flexibility in operation
- Achieve storage/discharge capacity across multiple time scales
- Reduce wear due to cycling, extend life
- Increase efficiency, reduce emissions
- Take advantage of grid market opportunities to increase revenue
- Eliminate stranded renewable electricity
- Support a stable, reliable, resilient electricity grid

Redox Flow Battery (RFB)



Advantages of RFBs



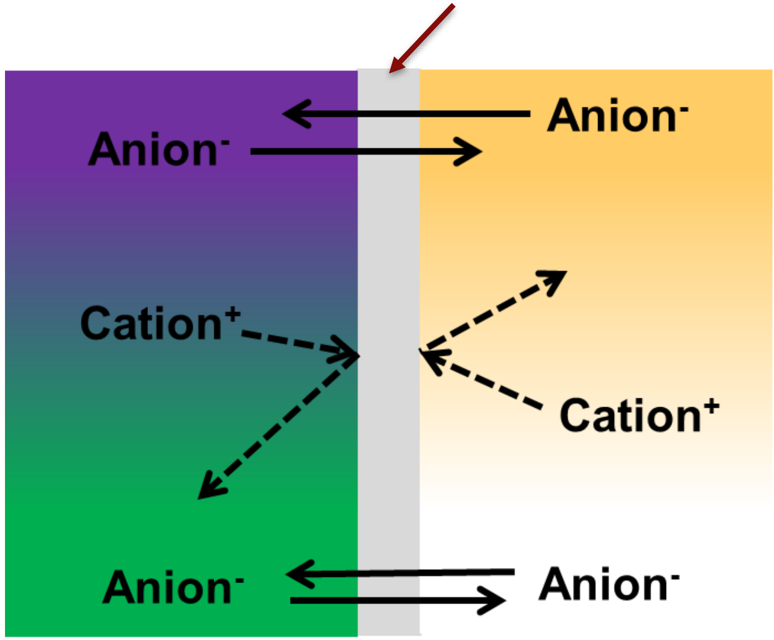


- Energy and power are decoupled
  - => greater design flexibility
  - => lower scale-up costs
- Rapid response
- Suitable for multiple time scales (minutes – weeks)
- Grid-scale demonstration projects underway (Vanadium type)

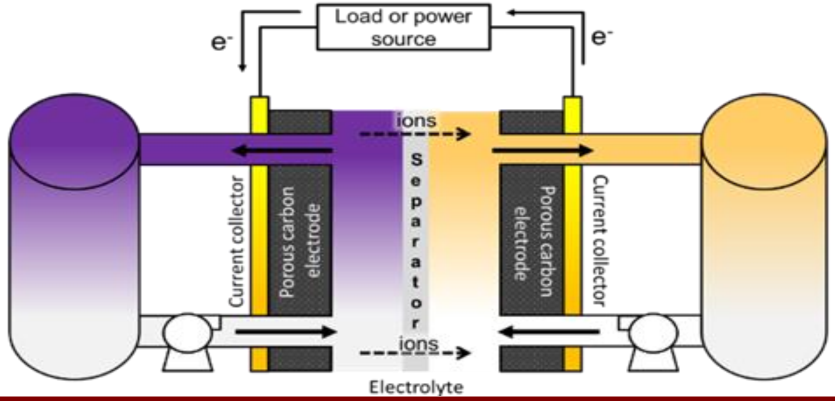
Ti-Ce electrode decoupled RFB

Anion Exchange Membrane (AEM)

Ti^{4+} (as TiO^{2+}) + e^- ↔ Ti^{3+}
(E_0 = 0.19V vs. SHE)



Ce^{4+} + e^- ↔ Ce^{3+}
(E_0 = 1.61V vs. SHE)

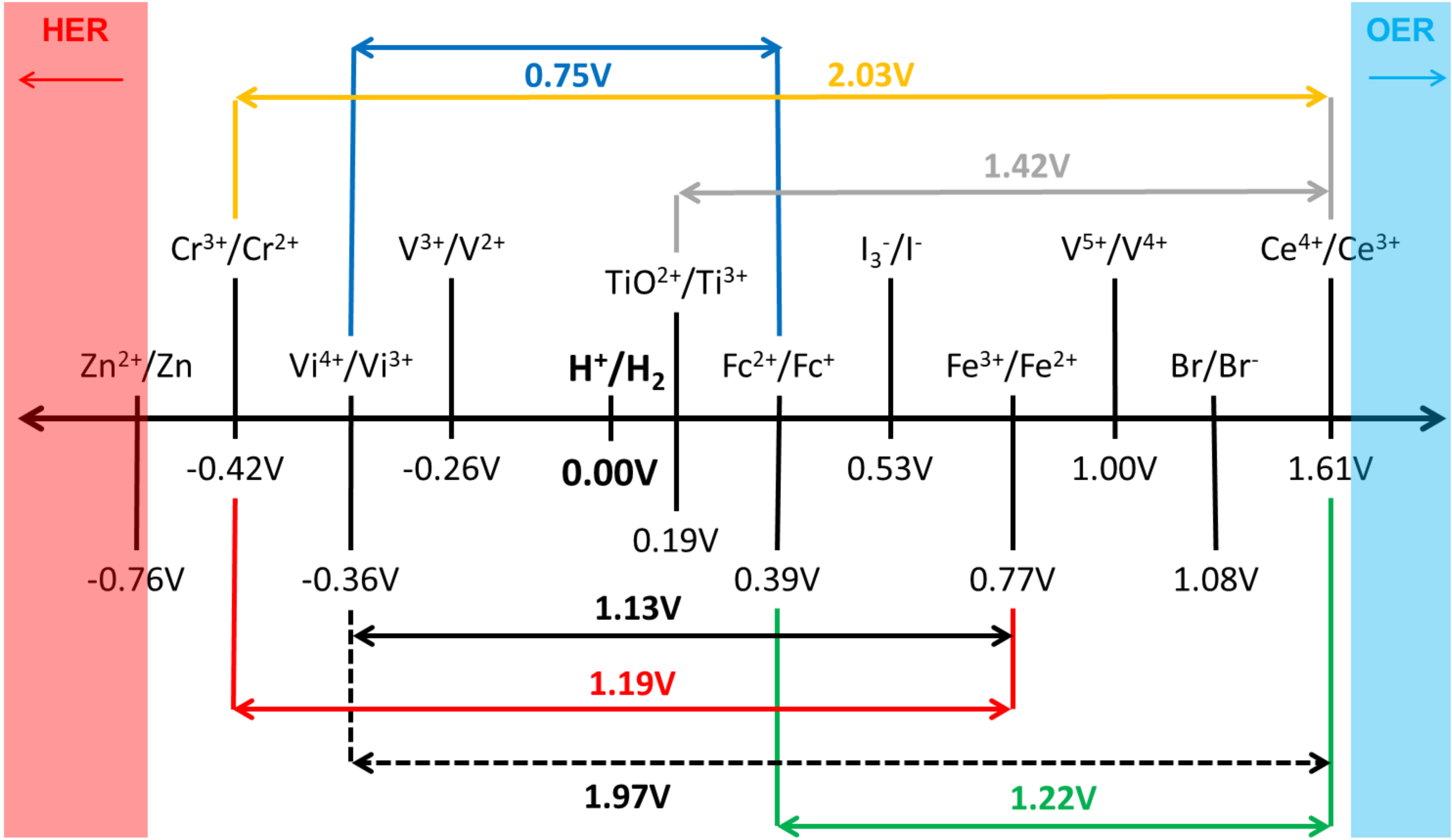


- Produced with H_2SO_4- or CH_3SO_3H-supported electrolyte
- Anion: SO_4^{-2} or $CH_3SO_3^-$

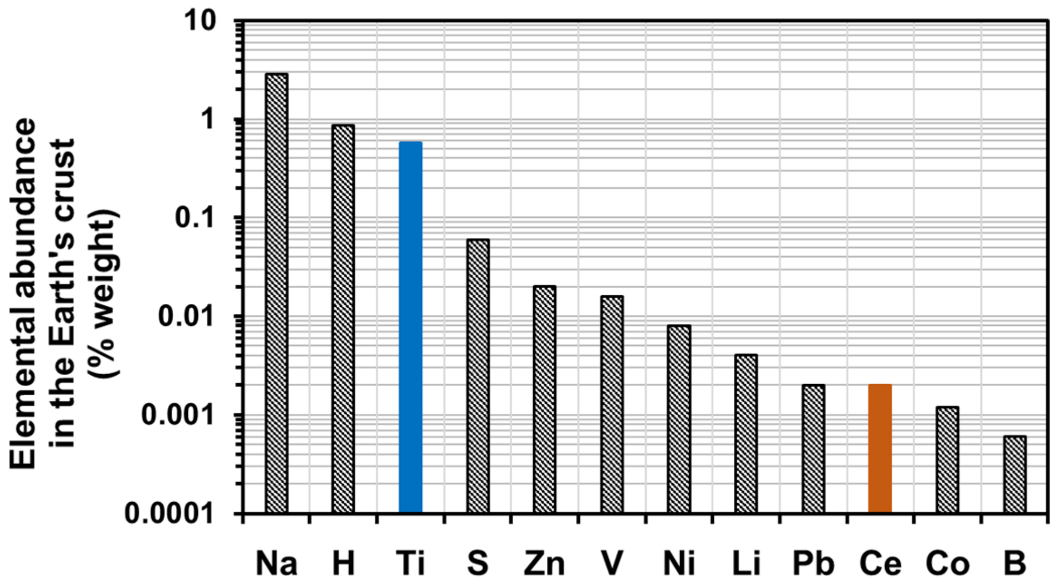
SHE: Standared Hydrogen Electrode

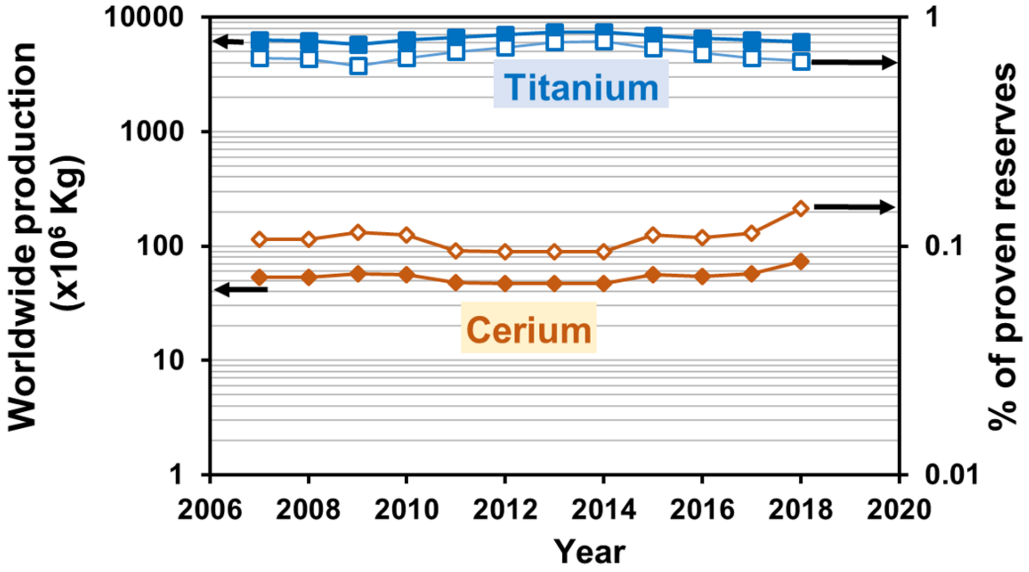
Advantages of Ti-Ce System

- Nominal Cell Voltage > 1V
- No phase change, solids precipitation
- Minimal potential for H_2 or O_2 evolution



Advantages of Ti-Ce System





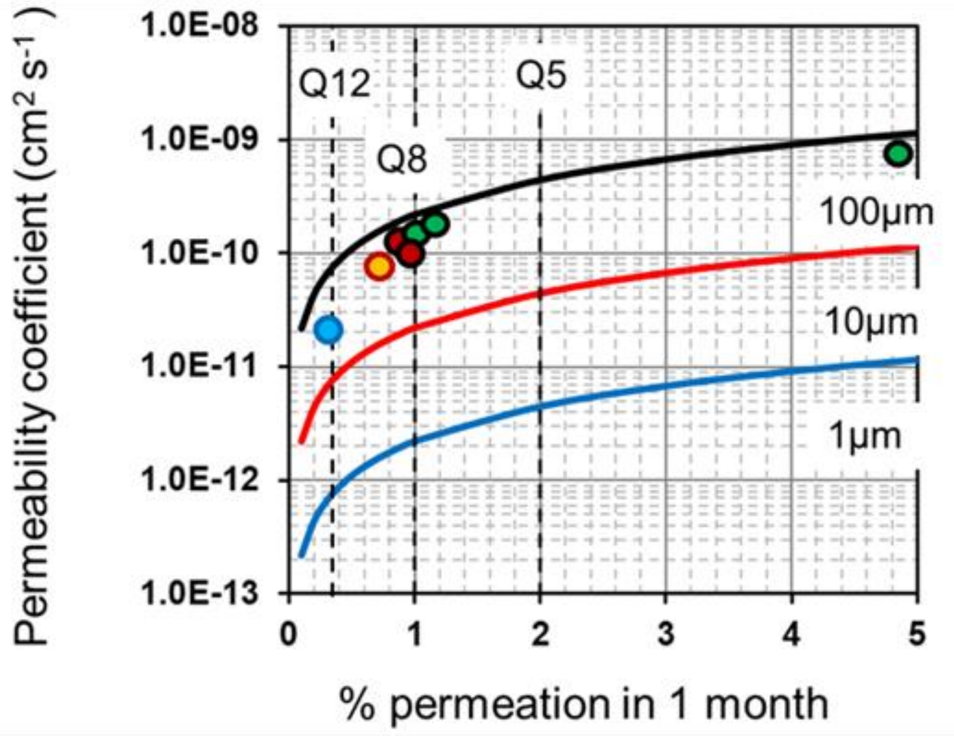
https://pubs.usgs.gov/fs/2002/fs087-02/

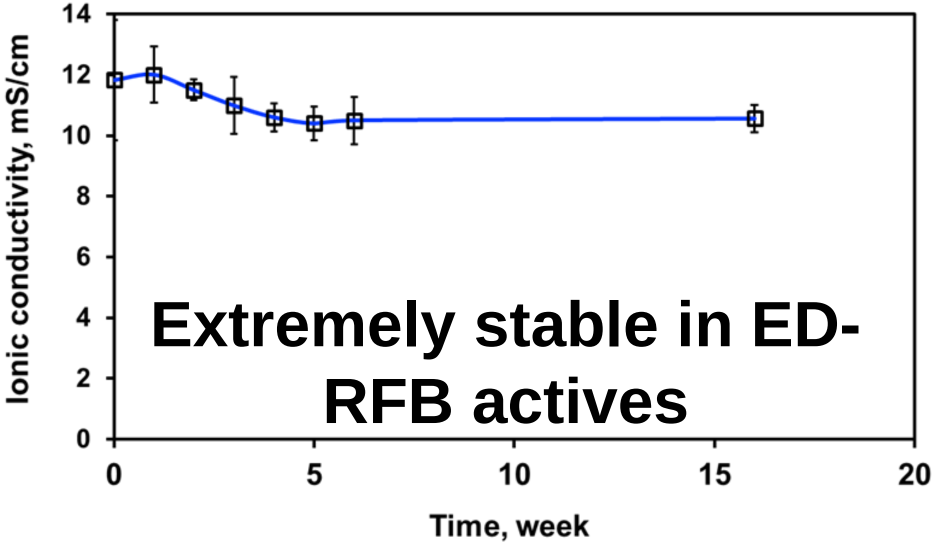
- ❑ Abundant active elements
- ❑ Lower material costs vs. All-V and V-Ce
- ❑ Proven reserves for >300x the total world electricity production (25,000 TWh/year)

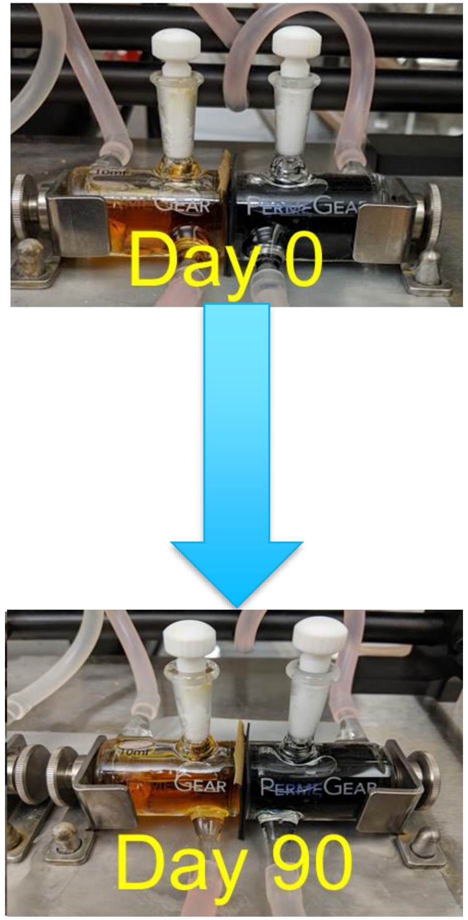
Anion Exchange Membrane (AEM)

- Key enabling technology
- Highly permselective to maintain separation of Ti and Ce species and prevent capacity fade

Highly selective

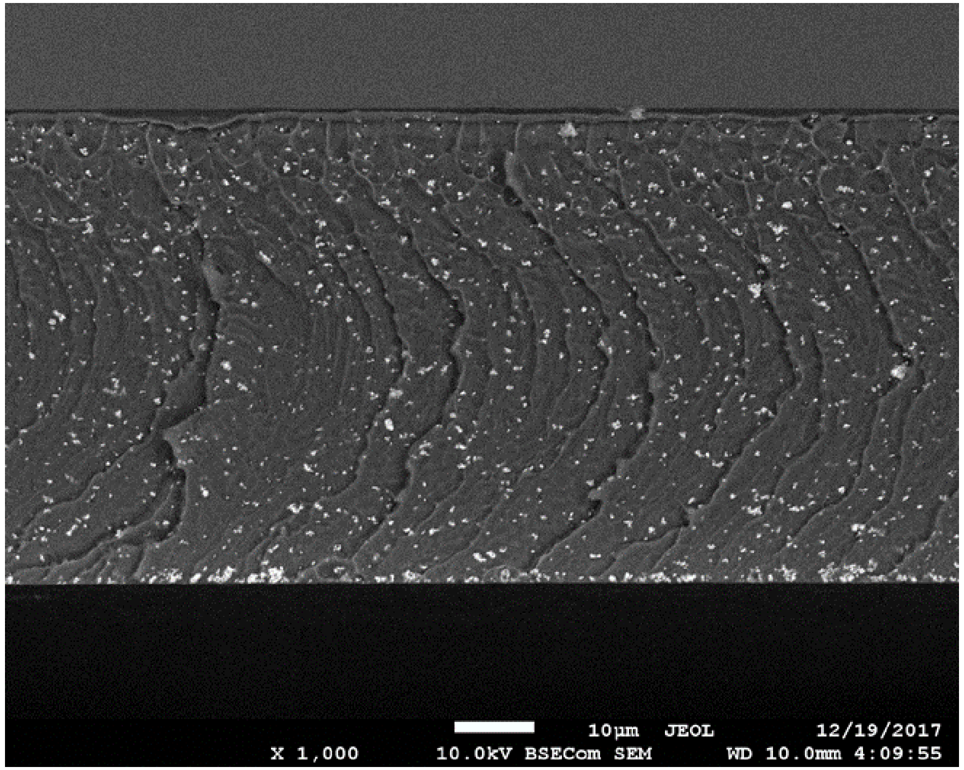




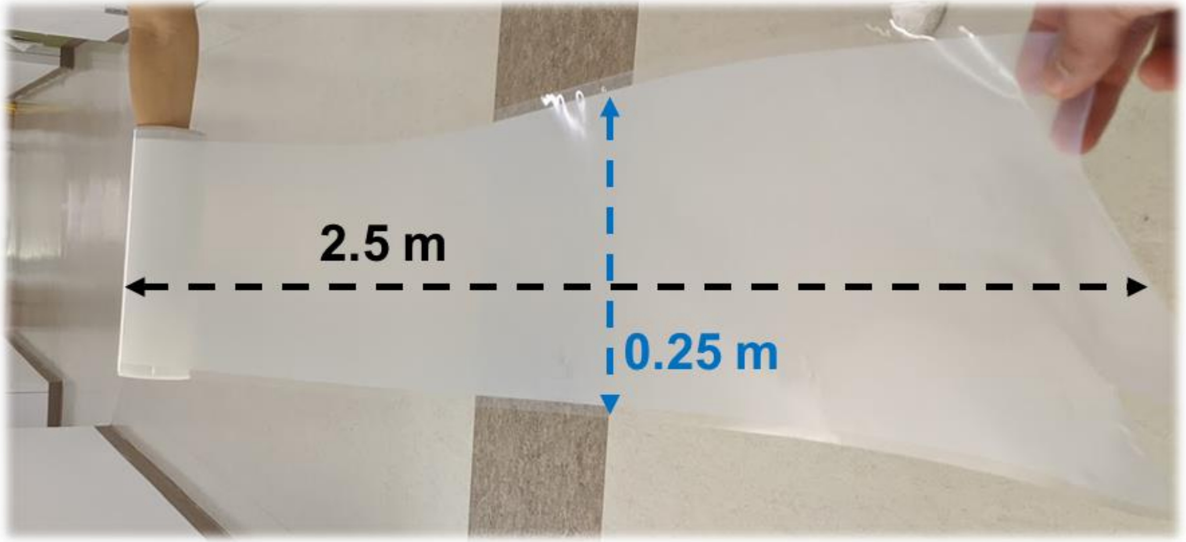


Anion Exchange Membrane (AEM)

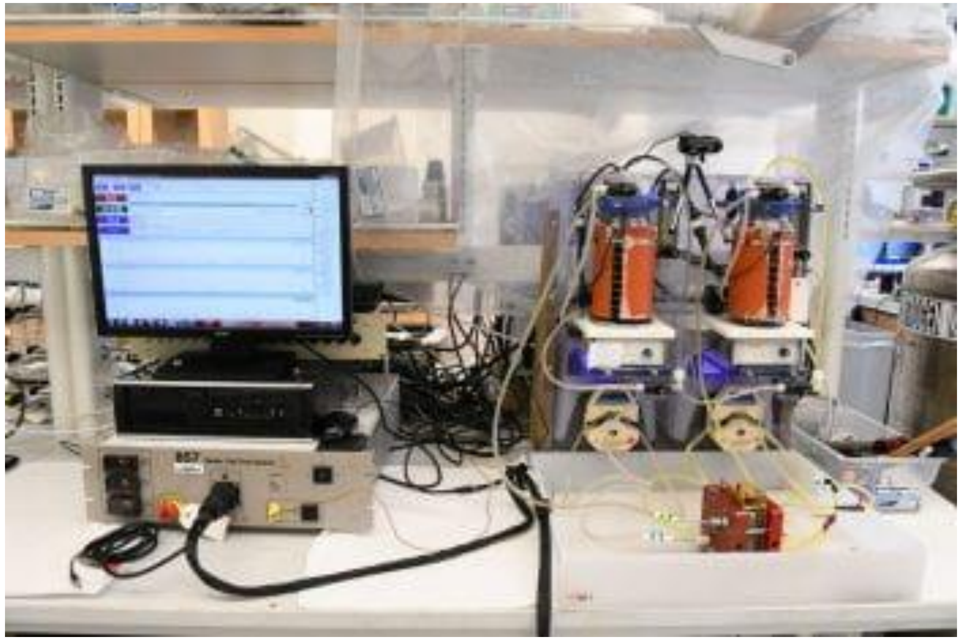
- Poly(ether ketone) doped with metal oxide nanoparticles to improve permselectivity



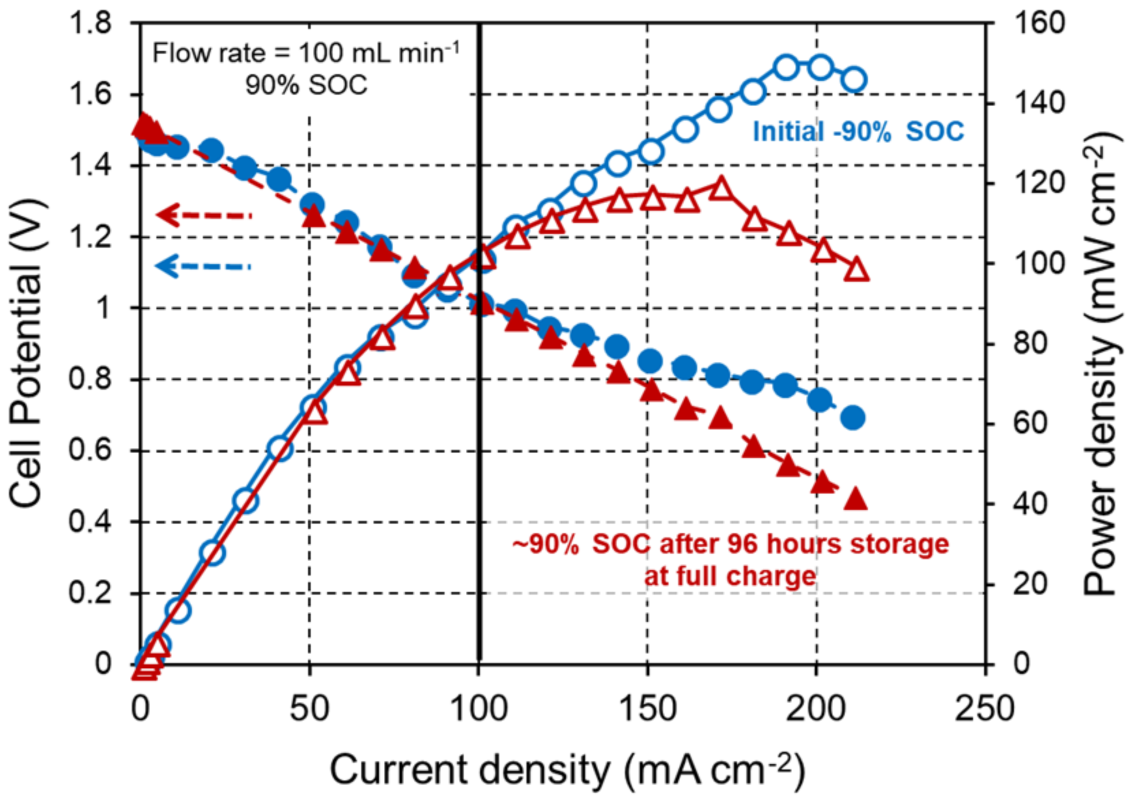
Made from 100cm^2 to roll-to-roll



Performance Test Results

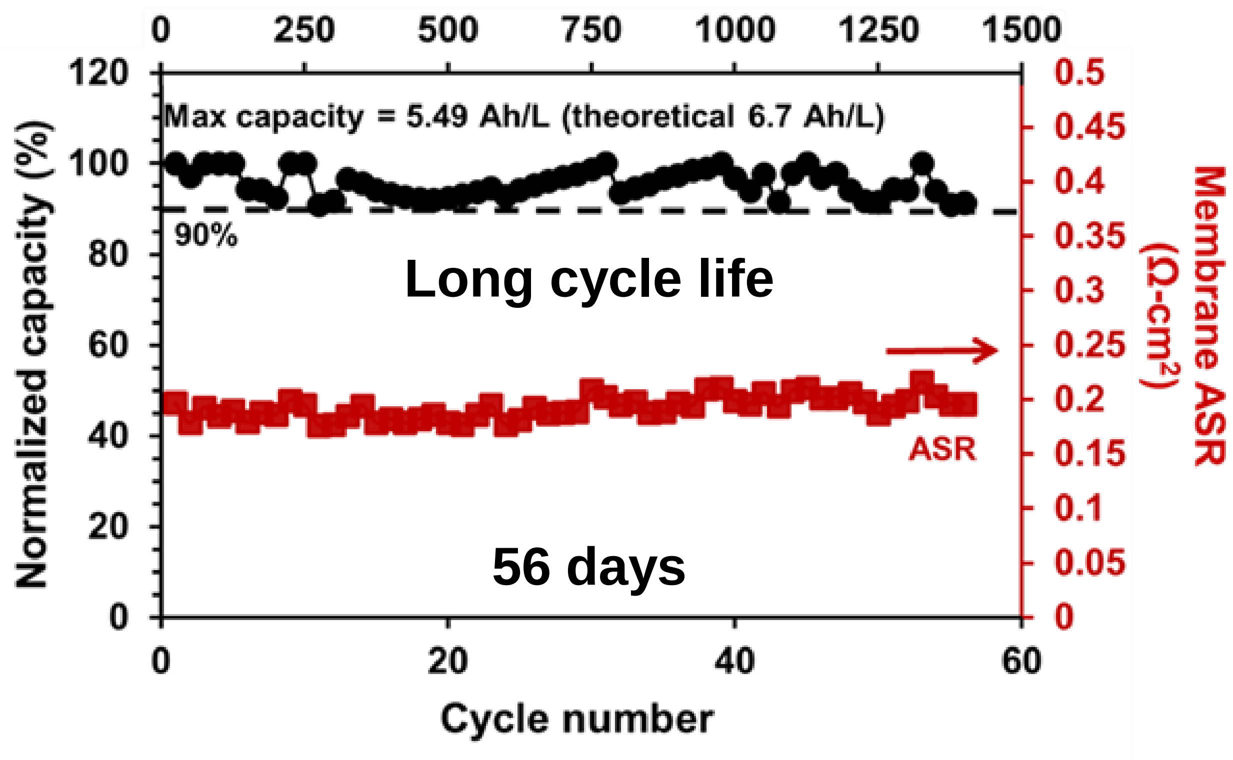


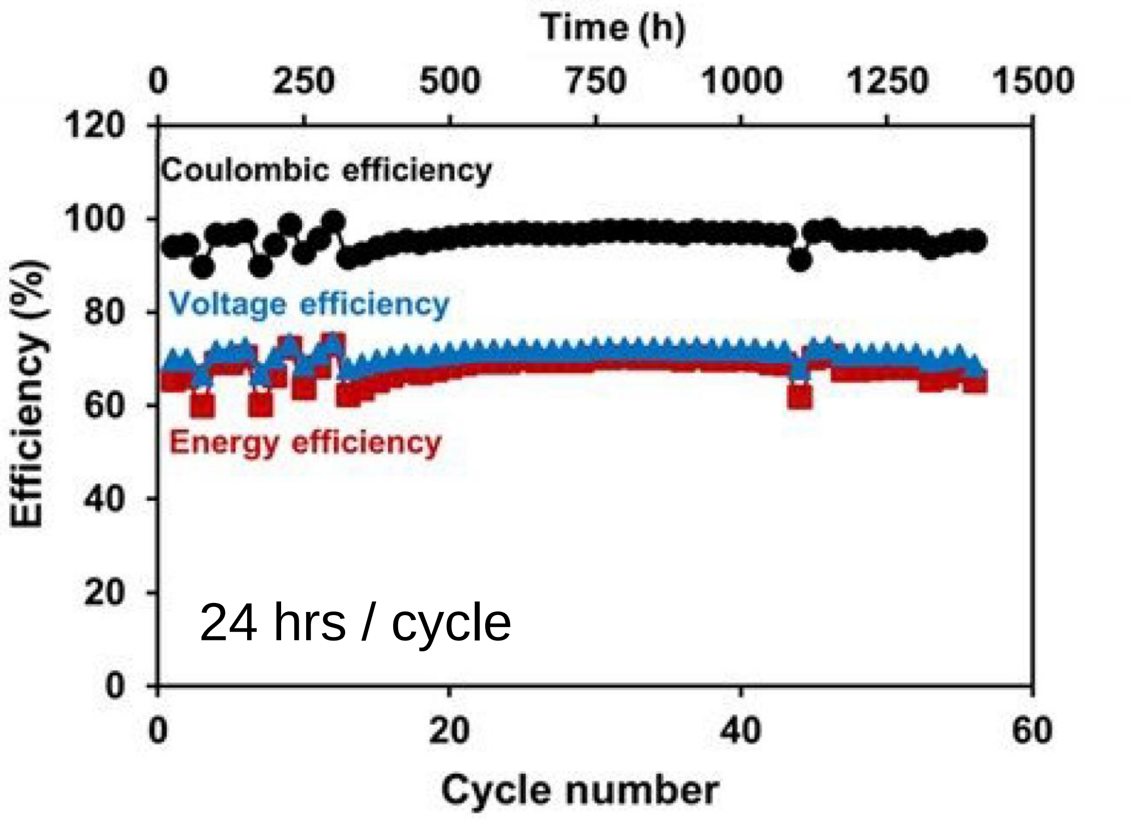
Test Cell



>3 day charge retention

Cycle Performance Results





Project Objectives

Overall Goal:

To advance the integration of a titanium-cerium electrode-decoupled redox flow battery (Ti-Ce ED-RFB) system with conventional fossil-fueled power plants through detailed technical and economic system-level studies and component scale-up and R&D.

Objective 1:

- Increase TRL from 4 to 5, by building and demonstrating a ED-RFB cell stack, with 3rd party validation, with following performance characteristics:
  - 0.2 A/cm2 current density
  - 400 cm2 cell size
  - Capable of 48-hr cycle duration
  - <5% capacity loss in 1- week standby

Project Objectives, Cont.

Objective 2:

- Demonstrate a pathway to achieve following cost targets for a utility-scale system:
  - Capex values of < \$500/kW (power) and < \$ 50/kWh (energy)
  - Levelized cost of storage (LCOS) of < \$0.05/kWh-cycle

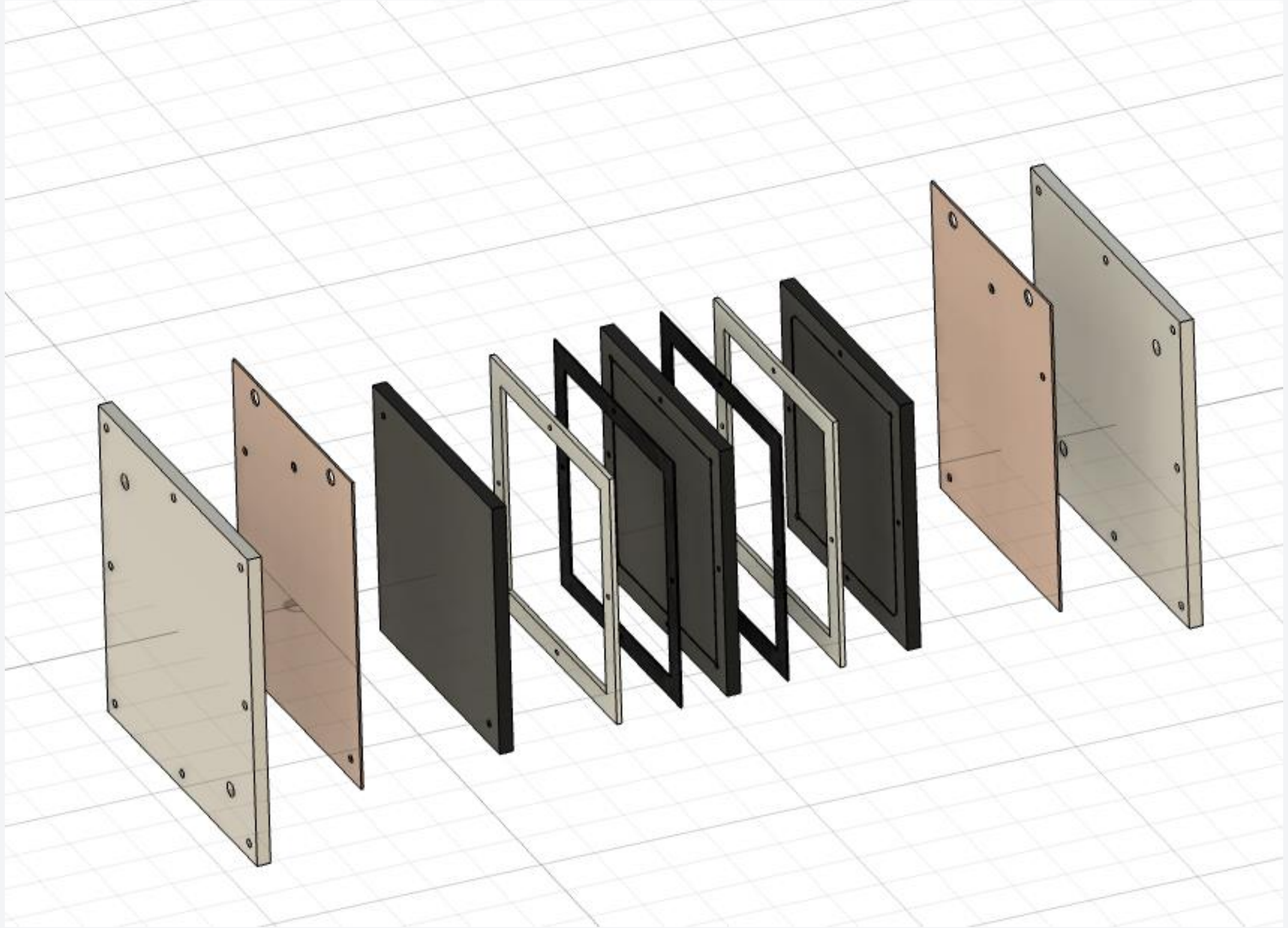
Objective 3:

- Reveal and quantify the benefits of co-locating the storage system within the fence-line of a fossil plant.

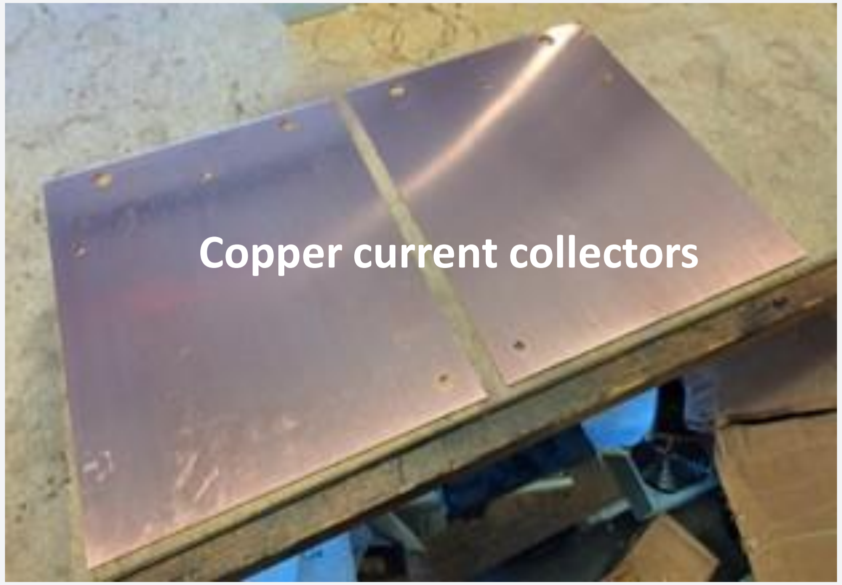
Objective 4:

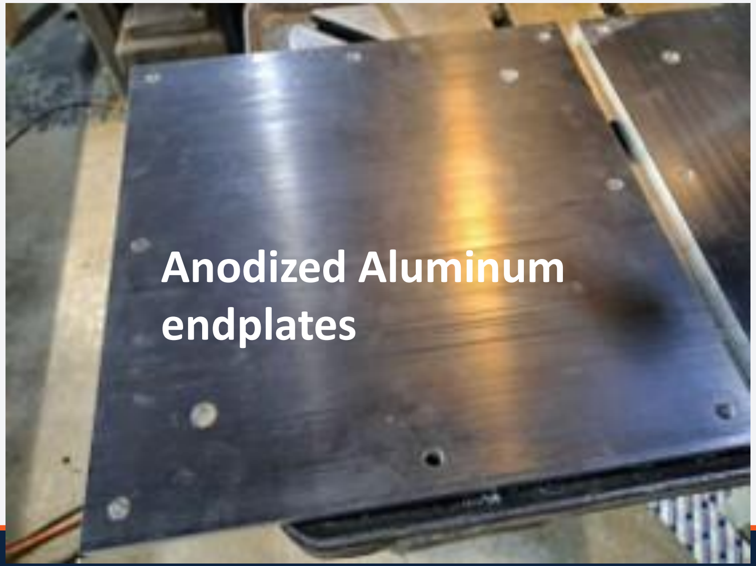
- Enable path to commercialization through market research, gap assessment, and technology maturation and commercialization planning

RFB scale-up to 400cm^2 active area



RFB scale-up to 400cm^2 active area

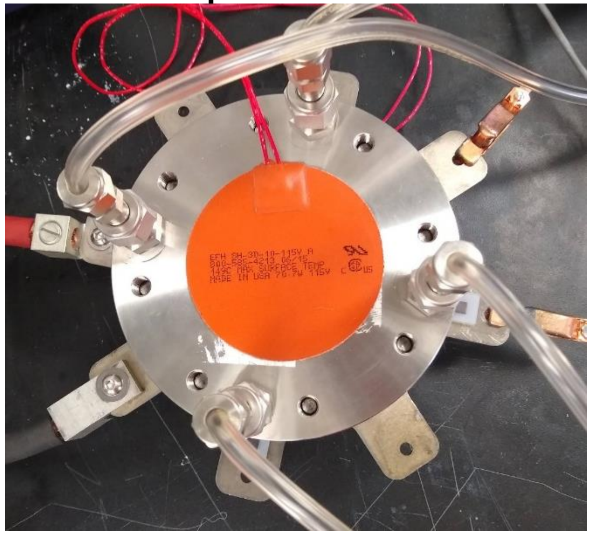


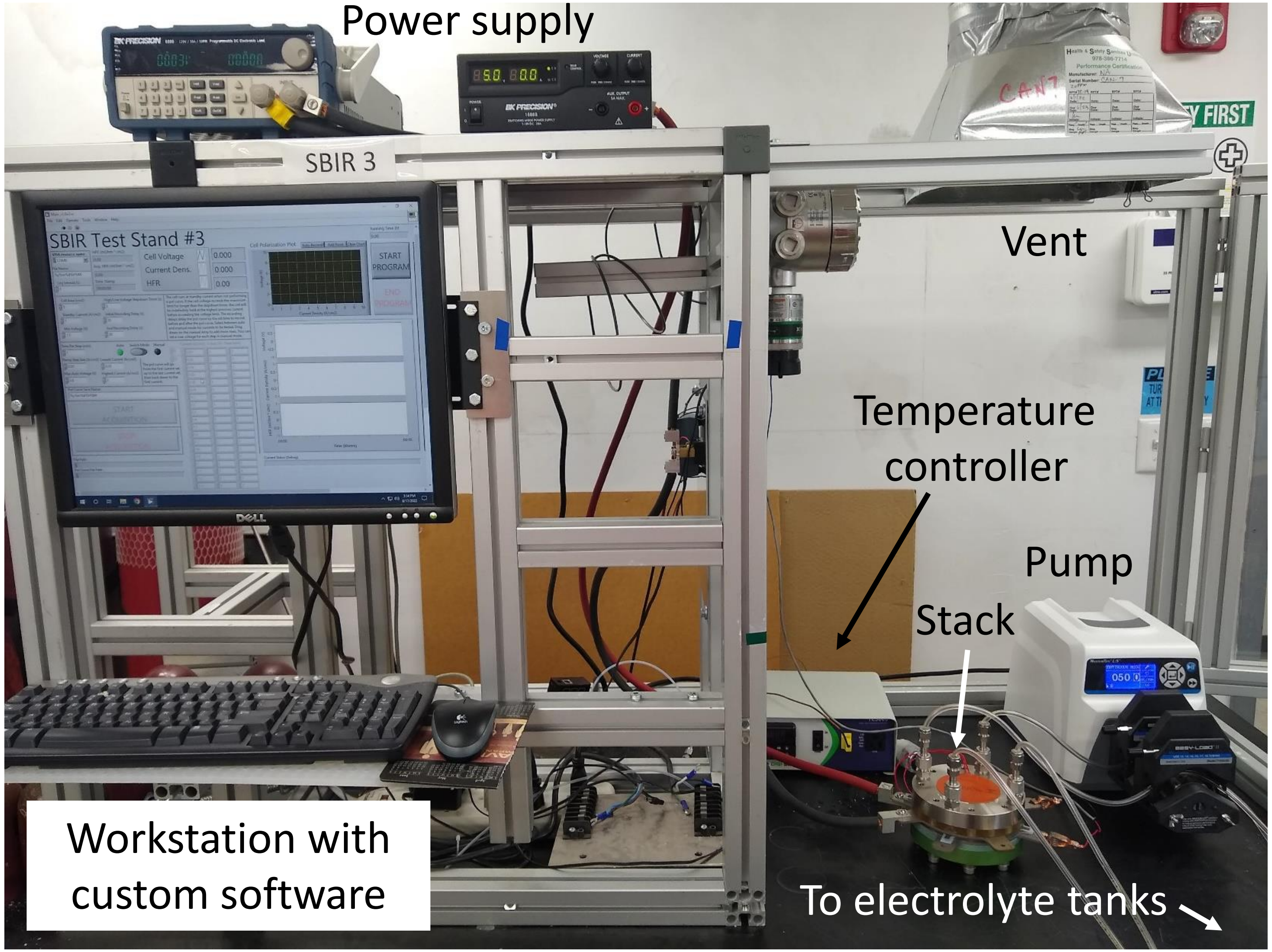


- ***Fabrication of scaled-up 400cm^2 active area RFB cell and stack complete.***
- ***Assembly ongoing for leak testing and commissioning***

Giner's flow battery testing

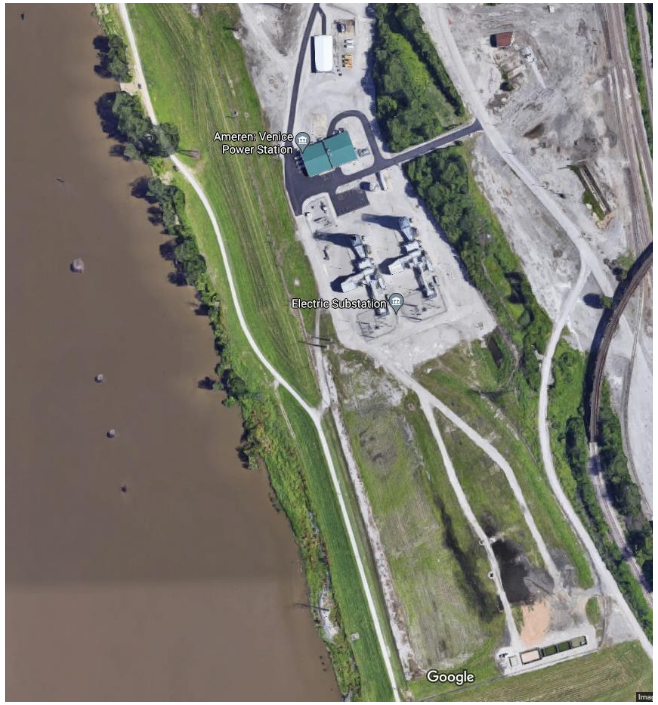
- Provides the ability to control/measure:
  - Voltage and current
  - Analyte and catholyte flow rates
  - Temperature
- Custom software enables:
  - Recording of cell voltage/current
  - Measuring of high frequency resistance (HFR)
  - Automated polarization curves





TEA Design Basis – Case Summary

Fossil Plant	Scenario A: No Storage	Scenario B: Short Duration	Scenario C: Intermediate Duration	Scenario D: Long Duration
1. Reference NGCC NETL Baseline Case 31A	1A	1B	1C	1D
2. Reference NGCC w/CDR NETL Baseline Case 31B	2A	2B	2C	2D
3 VEC* CT (simple cycle)	3A	3B	3C	3D
4. VEC NGCC	4A	4B	4C	4D



*VEC: Venice Energy Center (Ameren MO)

<u>Short Duration (0-2 hours):</u> grid services (frequency & voltage support), peak load, arbitrage

<u>Intermediate Duration (2-24 hours):</u> reduce daily plant cycling, arbitrage

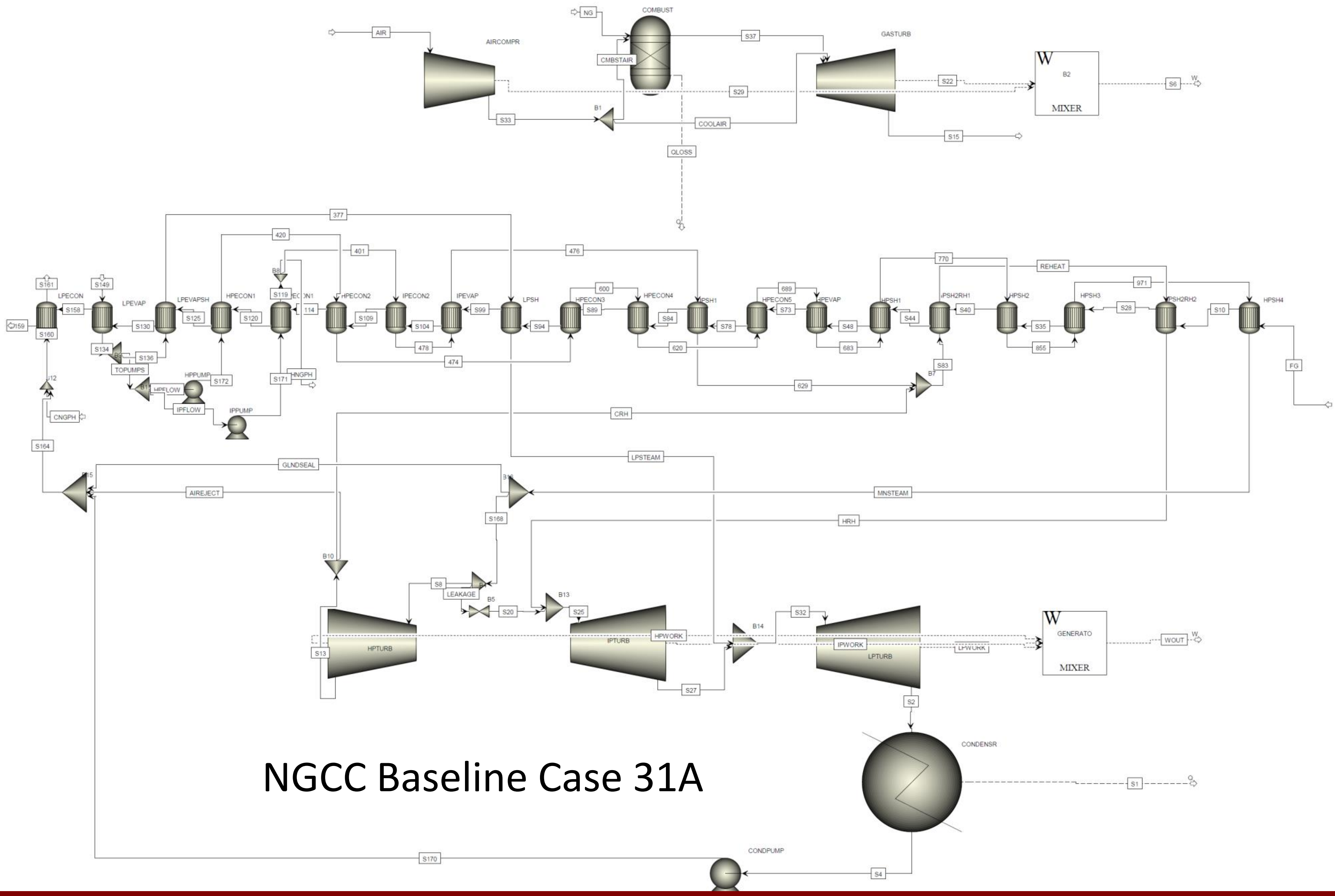
<u>Long Duration (24-48 hours):</u> multi-day weather or unplanned outage events

TEA Design Basis – Power Plant Specifications

Parameter	Ref. NGCC		VEC	
	Case 1	Case 2	Case 3	Case 4
Combust. Turbine gross output (MWe)	2 x 238		2 x 169	
HRSG Steam Cycle (psig/^{o}F/^{o}F)	2,393/1,085/1,085		N/A	1772/1050/1050
Steam Turbine Power (MWe)	263	213	N/A	185
CO_2 recovery load (MWe)	N/A	28	N/A	
Bal. of Plant Loads (MWe)	14	16	18	19
Plant Gross (MW)	740	690	338	523
Plant Net (MW)	727	646	320	504
LHV Plant Efficiency (%)	59.4	52.8	35.9	53.6
LHV Heat Rate (Btu/kWh)	5,743	6,462	9,493	6,363
LHV CT Efficiency (%)	39.0		35.9	
NOx Control	LNB & SCR		LNB	LNB & SCR
CT Turbine Specifications				
Type	F-Frame		F-Frame (501F-D2)	
Outlet Temperature (^{o}F)	1,156		1,116	
Inlet Temperature (^{o}F)	2470		2300	
Pressure Ratio	19.5		15.0	
Isentropic Efficiency (%)	87		87	
Plant Turndown Min Load (%)	22.0	N/A	50.0	22.0
Ramp Rate (MW/min)	80.0	N/A	tbd	tbd
Startup Time, RR Hot (min)	25	> 25	tbd	tbd
Electrical Specifications				
Grid Interconnect (kV)	345		138	

derived quantities

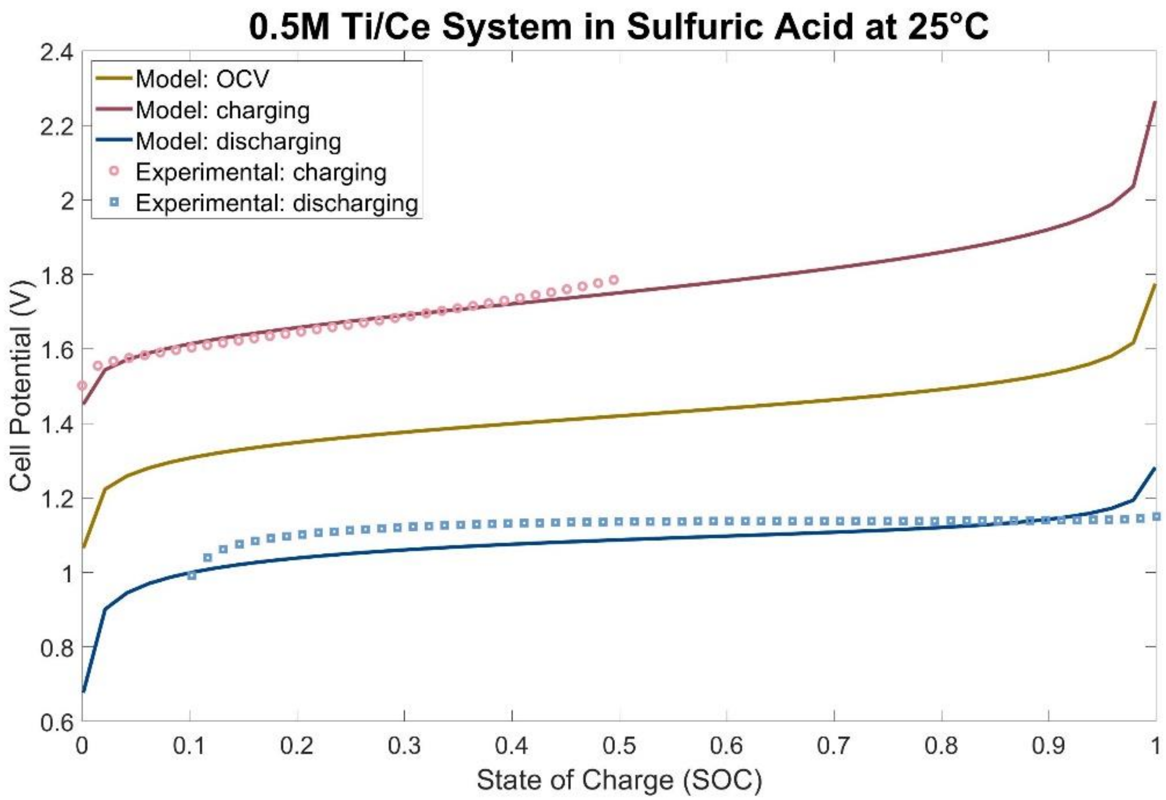
ASPEN Process Model



NGCC Baseline Case 31A

RFB Process Model Status

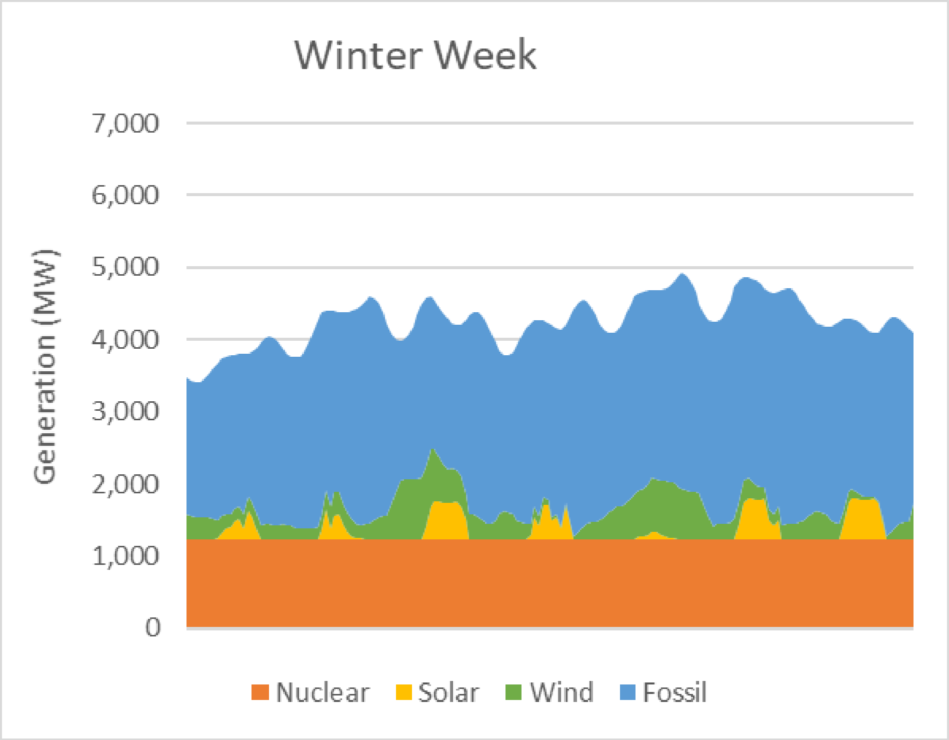
Inputs	Design Parameters: • Parameters specific to stack configuration • Parameter specific to electrolyte reservoirs • Parameters specific to operating conditions Material/Equipment Specifications: • Parameters sourced from manufacturers • Parameters sourced from literature • Parameters measured experimentally
Model	• **Electrochemical model** • Shunt current model • Pumping loss model
Outputs	• **Cell potential vs. state of charge relation** • Cell efficiency sensitivity to design parameters • Flow channel cross-sectional area for minimal power losses

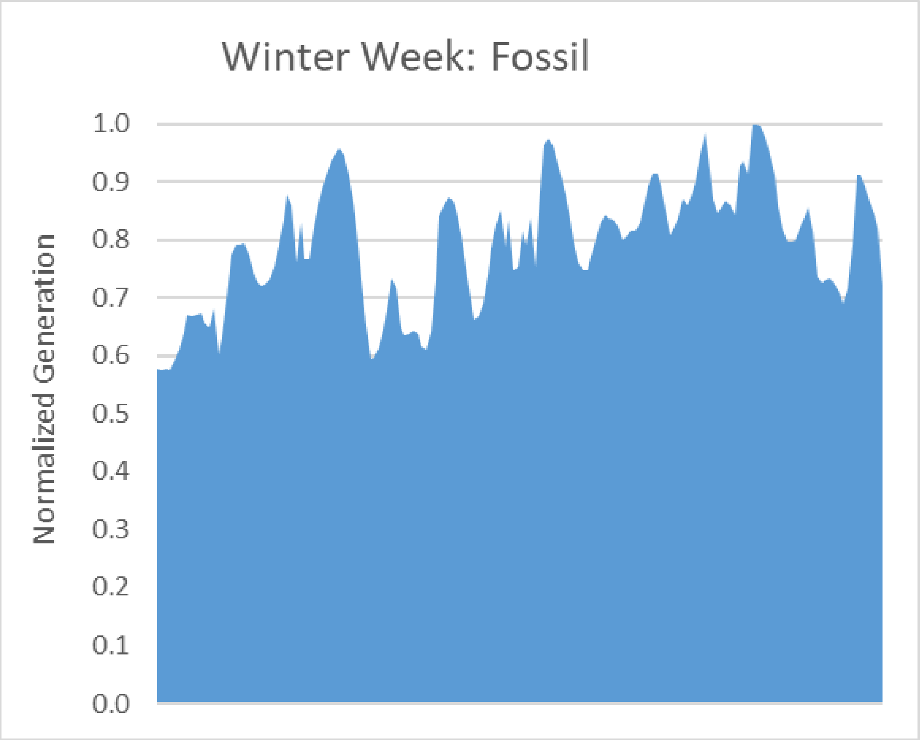


TEA Design Basis – Baseline Load Profile

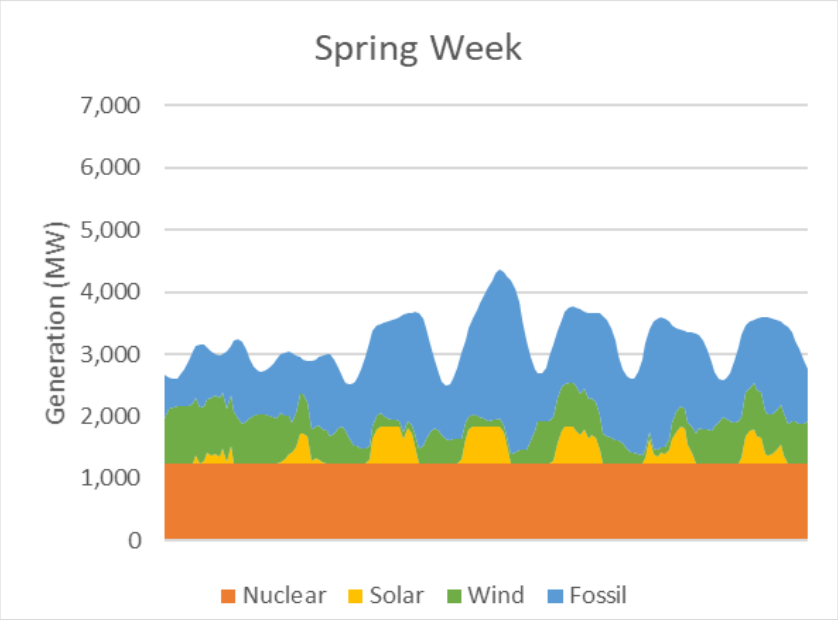
Hypothetical power generation fleet located in Midwest consisting of

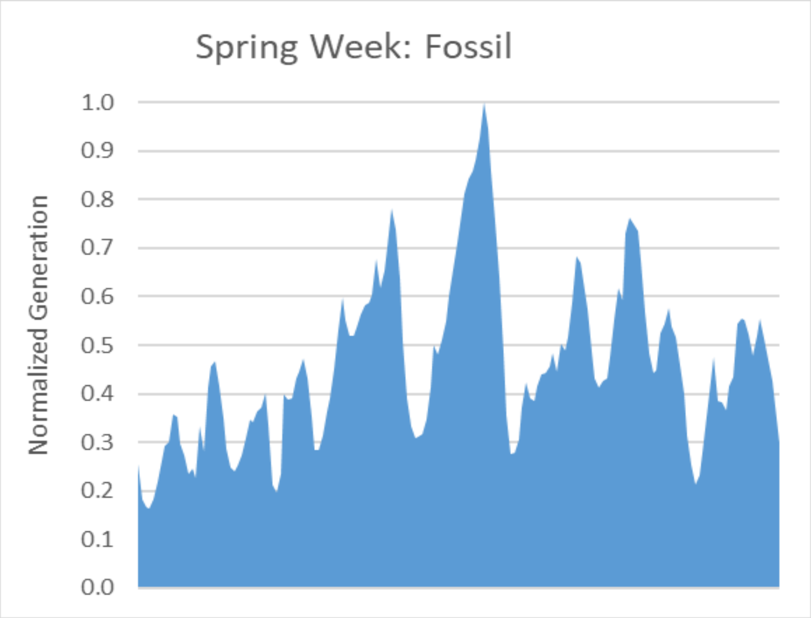
- 600 MW of solar (nameplate capacity)
- 1200 MW of wind (nameplate capacity)
- 1200 MW of baseline nuclear.

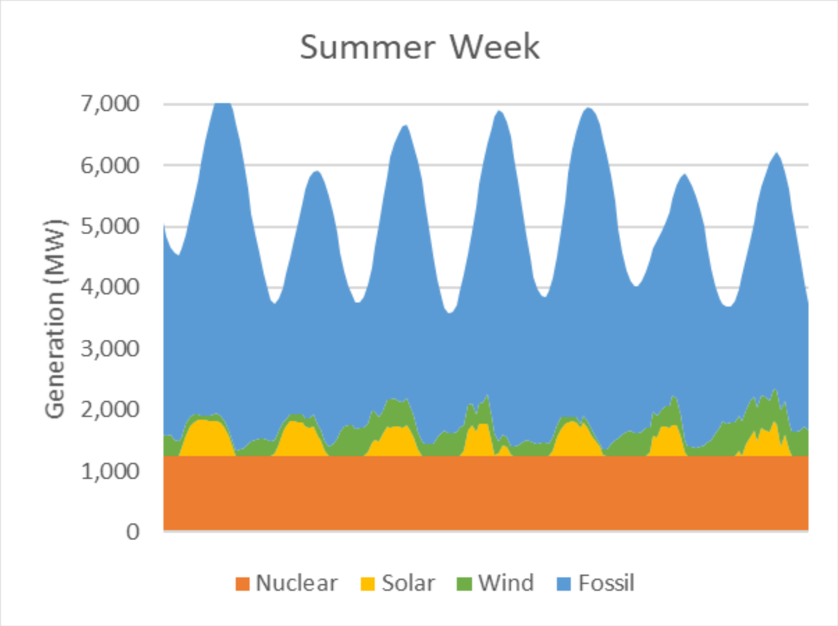


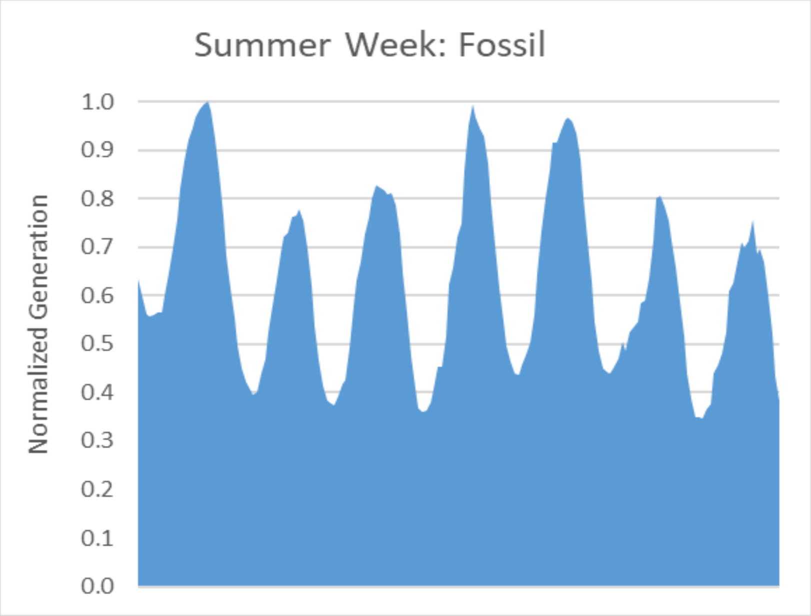


TEA Design Basis – Baseline Load Profile

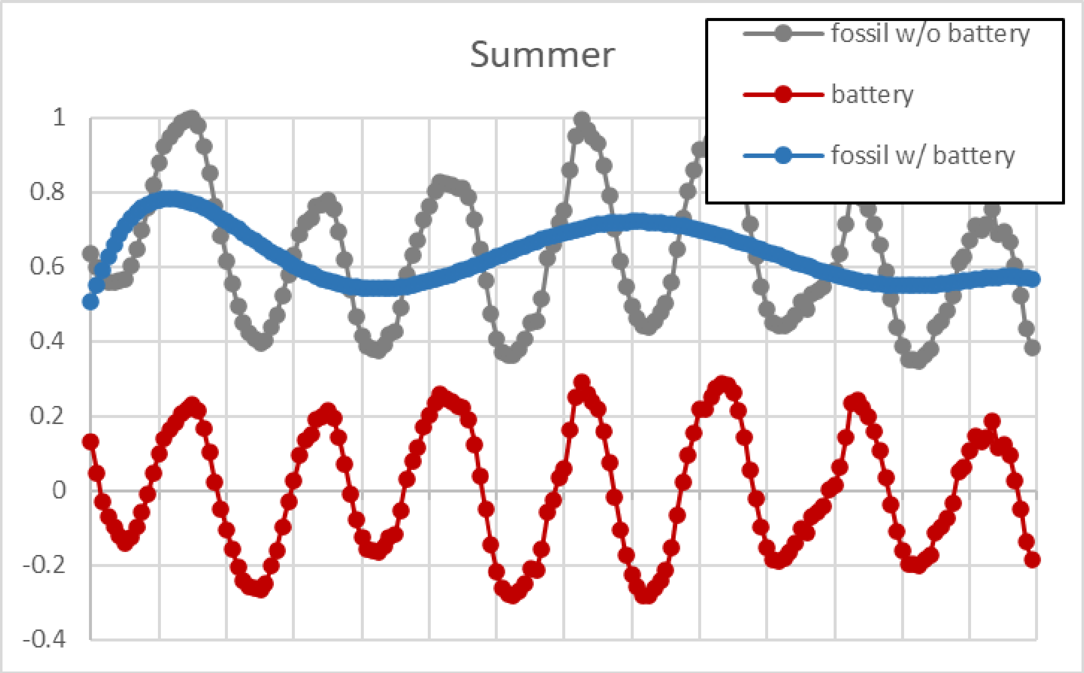


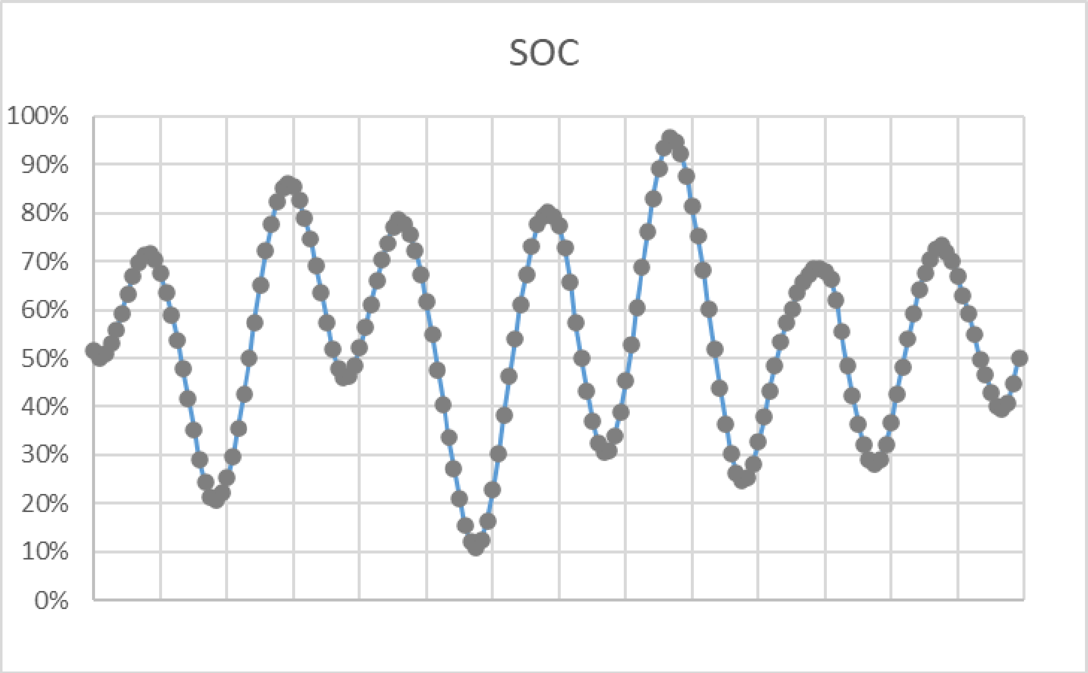






Battery Sizing – Medium Duration Storage (max 24 hrs)



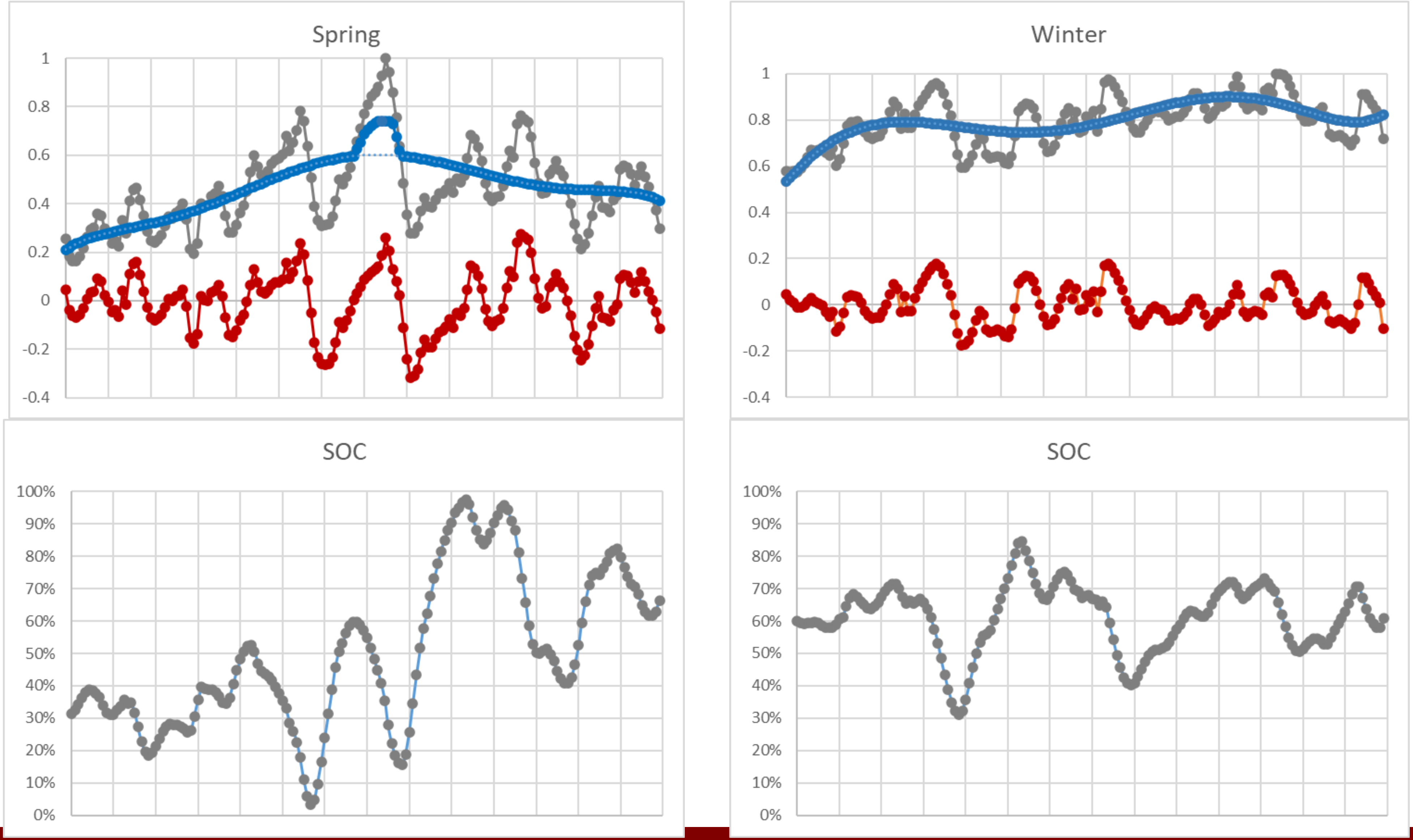


scenario:

- batteries solely responsible for daily cycles
- fossil ramps according to multi-day load trends

Fossil Plant / Size	Battery Max Power (MW)	Battery Capacity (MW-hr)
1,000 MW	300	3,500
NETL Baseline NGCC: 727 MW	218	2,545
VEC NGCC: 504 MW	151	1,764

Battery Sizing – Medium Duration Storage (max 24 hrs)

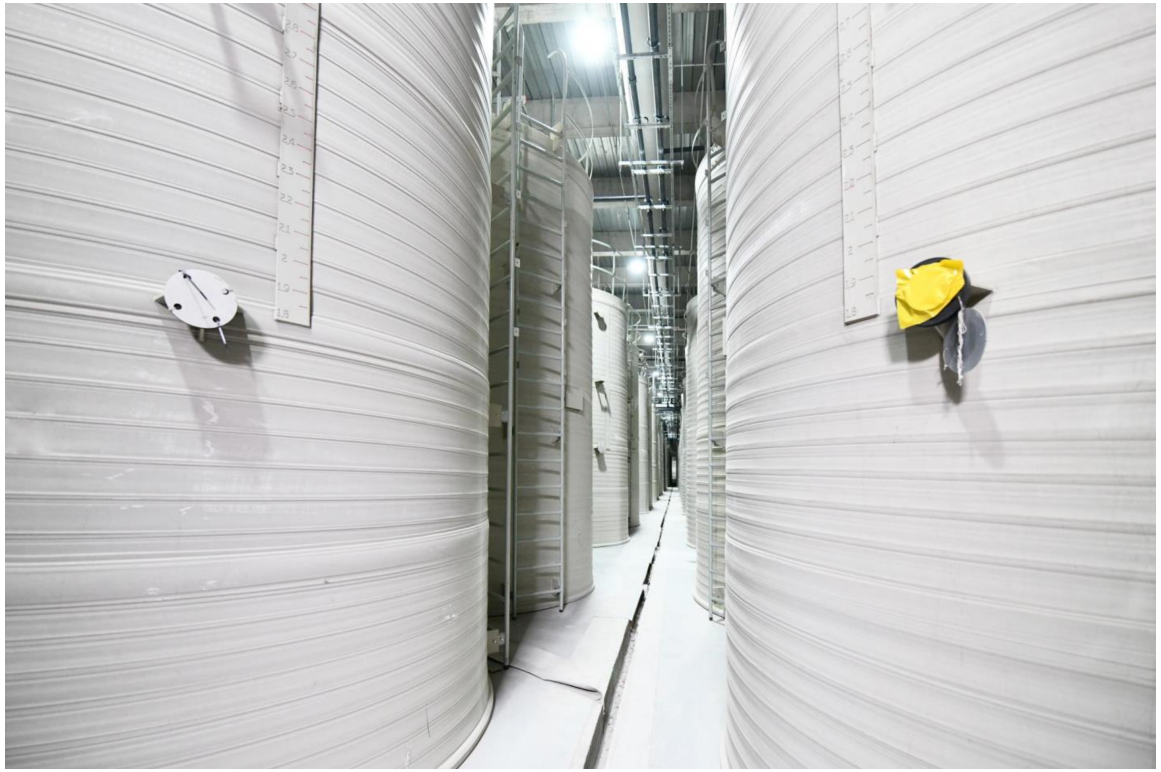


Electrolyte Storage Tank Sizing

Assumptions:

- Operating voltage = 1 V
- Electrolyte concentration = 1 M

=> **10 gallons/kWhr (per electrolyte)**



<u>Example</u>:
Dalian Flow Battery Energy Storage
Peak-Shaving Power Station
100 MW/400 MWh

Rongke Power Co. Ltd.

https://english.cas.cn/newsroom/research_news/chem/202205/t20220531_306054.shtml

Ameren Venice Energy Center

1,000 MWh Installation

10,000,000 gal, Qty 100 100,000 gal tanks (x2)
(Diam 30 ft, Ht 19 ft)

Installed Cost Analysis

<u>Reference Methodology:</u>

2022 Grid Energy Storage Technology Cost and Performance Assessment, PNNL-33283

Our model matches DOE's all-V RFB model –

Power – 1MW; Duration – 4h; 1 molar electrolyte solution concentration; 100 mW/cm^2 power density.

Same PCS, ESS and integrator margins assumed.

Ti-Ce RFB cost estimates (supplier cost)

– no optimizing assumptions

	1MW/4MWh	10MW/40MWh
DC system ($/kWh)	267	248
AC installed cost ($/kWh)	401	345

<u>~$80-$100/kWh difference compared to all-V RFB</u>

Thank you

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Acknowledgment: This material is based upon work supported by the Department of Energy National Energy Technology Lab under Award Number(s) DE-FE0032011.

PNNL All Vanadium Installed Cost Analysis

		1 MW								10 MW							
		2 hr		4 hr		10 hr		24 hr		2 hr		4 hr		10 hr		24 hr	
		2021	2030	2021	2030	2021	2030	2021	2030	2021	2030	2021	2030	2021	2030	2021	2030
ESS Installed Cost / ESS / Storage System	DC Storage Block ($/kWh)	$369.30	$306.96	$276.59	$229.89	$220.96	$183.66	$199.32	$165.67	$351.72	$292.34	$263.42	$218.95	$210.44	$174.91	$189.83	$157.79
	DC Storage BOS ($/kWh)	$73.86	$55.15	$55.32	$41.31	$44.19	$33.00	$39.86	$29.77	$70.34	$52.53	$52.68	$39.34	$42.09	$31.43	$37.97	$28.35
	Power Equipment ($/kW)	$154.86	$137.00	$154.86	$137.00	$154.86	$137.00	$154.86	$137.00	$133.00	$117.65	$133.00	$117.65	$133.00	$117.65	$133.00	$117.65
	C&C ($/kW)	$40.00	$29.87	$40.00	$29.87	$40.00	$29.87	$40.00	$29.87	$7.80	$5.82	$7.80	$5.82	$7.80	$5.82	$7.80	$5.82
	Systems Integration ($/kWh)	$79.59	$67.53	$56.34	$47.81	$42.40	$35.97	$36.97	$31.37	$73.58	$62.43	$52.55	$44.59	$39.93	$33.88	$35.03	$29.72
	EPC ($/kWh)	$93.03	$78.93	$65.54	$55.61	$49.05	$41.62	$42.64	$36.18	$84.91	$72.04	$60.58	$51.40	$45.98	$39.01	$40.30	$34.20
	Project Development ($/kWh)	$106.98	$90.77	$75.38	$63.96	$56.41	$47.87	$49.04	$41.61	$97.64	$82.85	$69.66	$59.11	$52.88	$44.87	$46.35	$39.33
	Grid Integration ($/kW)	$30.94	$26.25	$30.94	$26.25	$30.94	$26.25	$30.94	$26.25	$25.00	$21.21	$25.00	$21.21	$25.00	$21.21	$25.00	$21.21
	Total Installed Cost ($/kWh)	$835.66	$695.90	$585.62	$486.85	$435.59	$361.42	$377.25	$312.65	$761.08	$634.53	$540.34	$449.55	$407.89	$338.57	$356.39	$295.41
	Total Installed Cost ($/kW)	$1,671	$1,392	$2,342	$1,947	$4,356	$3,614	$9,054	$7,504	$1,522	$1,269	$2,161	$1,798	$4,079	$3,386	$8,553	$7,090

https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf